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CAVITY STABILITY DURING GAS JET IMPINGEMENT ON LIQUID SURFACES IN WEIGHTLESSNESS

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16. Abstract

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CAVITY STABILITY DURING GAS JET IMPINGEMENT ON LIQUID SURFACES IN WEIGHTLESSNESS

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SUMMARY

As a part of the continuing research into the behavior of liquids in weightlessness, an experimental investigation was conducted in a drop tower to determine the cavity stability characteristics for a laminar parabolic gaseous nitrogen jet impinging normally on a water surface. The critical gas jet velocity for cavity stability was correlated in terms of a critical modified Weber number and the Reynolds number. The contact angle on the test container surface was maintained at 90° such that the liquid-gas interface was completely flat during weightlessness.

INTRODUCTION

The NASA Lewis Research Center has been conducting basic and applied research to study the dynamic behavior of liquids under reduced gravitational conditions. As a part of this research program, the dynamic effects of a gas jet impinging on a liquid surface were studied. A knowledge of the interaction of the jet with the liquid surface is required for the prediction of gas penetration, spraying, free bubble motion in the liquid, and gas blow-through. Gases impinging on liquids are encountered in a wide variety of applications ranging from a pressurant gas impinging on a liquid draining from its container to a rocket exhaust gas impinging on the surface of a body of water during lift-off.

The dynamics of a laminar parabolic gaseous jet impinging normally on a liquid surface during weightlessness were studied in reference 1. In that work, the gas penetration depth into the liquid surface was correlated with the jet momentum and the liquid surface tension. The results of that work indicate that, during the impingement phenomena at gas velocities exceeding some critical value (for which a correlation with system parameters was not attempted), one or more bubbles will pinch off from the gas cavity. These bubbles became entrained in the bulk liquid as free bubbles because of the absence of buoyancy forces in weightlessness. For many liquid-gas systems, the existence of free bubbles in the bulk liquid is intolerable. For such systems, it is important to be able to predict the critical velocity at which bubble pinch-off occurs.

The purpose of this report is to present the results of an experimental investigation (conducted at the NASA Lewis Research Center) concerning gas jet impingement on a liquid surface during weightlessness to correlate the inception of bubble pinch-off with known system parameters. The study was conducted employing laminar parabolic jets of nitrogen as the test gas and water as the test liquid. The distance between the liquid surface and the nozzle was preset to remain less than three nozzle diameters in order to minimize jet spreading.

SYMBOLS

a_o	cross-sectional area of nozzle, cm^2
d	diameter of cylindrical gas cavity, cm
d_o	nozzle diameter, cm
H	distance between nozzle tip and liquid surface, cm
h_p	penetration depth into liquid measured along axis of symmetry, cm
L	nozzle length, cm
M	jet momentum flux, dynes; N
Re	Reynolds number, $\rho_g \overline{V}_J d_o / \mu_g$
$\overline{V}_I$	average jet velocity at instability, cm/sec
$\overline{V}_J$	average jet velocity, cm/sec
We_M	modified Weber number, $\overline{V}_J^2 d_o \rho_g / \sigma_l$
λ	wavelength, cm
μ	viscosity, cP
ρ	density, g/cm^3
σ	surface tension, dynes/cm; N/cm

Subscripts:

cr	critical
g	gas
l	liquid
par	parabolic profile

ANALYSIS

Inviscid Stability Model

During weightlessness, the gas that exits from the circular nozzle impinges on the liquid surface, which results in the gas cavity shown schematically in figure 1. In reference 1, the average depth of penetration h_p was correlated with the jet momentum M

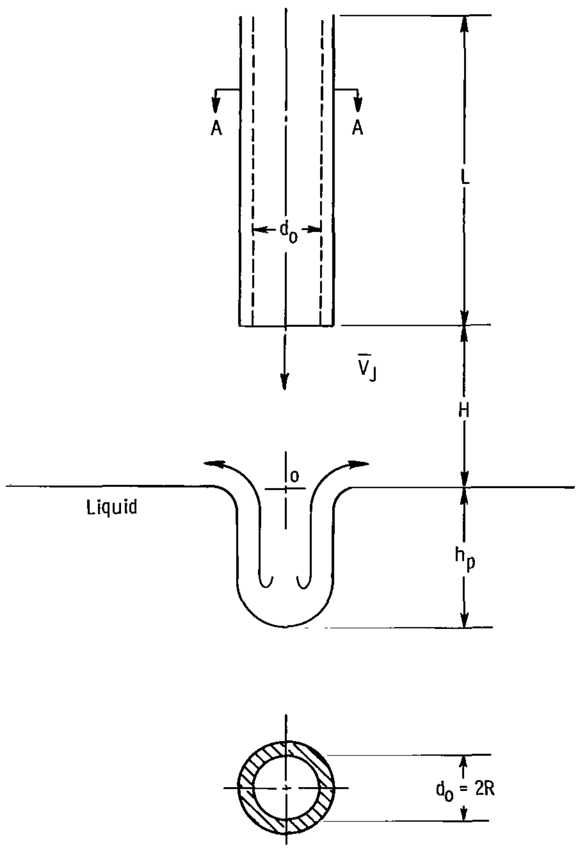


Figure 1. - Diagram of nozzle and gas cavity defining variables.

and the liquid surface tension σ_l through the following relation, in which the exiting gas had an initially parabolic velocity profile:

$$h_p = 1.67 \frac{M_{par}}{\sigma_l} \tag{1}$$

The length of nozzle L required for the existence of a fully developed parabolic velocity profile in a circular nozzle of diameter d_o is given in reference 2 as

$$\frac{L}{d_o} \geq 0.0145 \, Re \tag{2}$$

In this equation, the Reynolds number Re is the ratio of inertial to viscous forces, based on conditions at the nozzle outlet. Since the momentum of a parabolic jet is known from reference 3, equation (1) can be expressed as

$$\frac{4}{3} \rho_g a_o \overline{V}_J^2 = 0.6 \, \sigma_l h_p \tag{3}$$

Replacing a_o by $(\pi/4)d_o^{\,2}$ allows equation (3) to be rewritten in the form

$$\frac{\overline{V}_J^2 d_o \rho_g}{\sigma_l} = \frac{0.57 \, h_p}{d_o} \tag{4}$$

Equation (4), which is simply another form of equation (1), yields a relation for the depth of penetration during weightless conditions for a stable gas cavity.

When the average jet velocity becomes sufficiently high, bubbles pinch off from the cavity (as observed in ref. 1), which results in small bubbles being entrained in the bulk liquid since the buoyancy forces are absent. In a classical inviscid study made by Rayleigh (ref. 4), it was shown that a cylindrical cavity of gas of diameter d surounded by a liquid possesses an optimum ratio of breakup wavelength to diameter. Rayleigh showed that this wavelength-to-diameter ratio is given by $\lambda/d = 6.48$. If it is assumed that at the onset of instability the depth of penetration h_p corresponds to the wavelength λ in Rayleigh's notation, then a relation for predicting a stable cavity can be obtained by substitution of $h_p/d_o = 6.48$ into equation (4):

$$\frac{\overline{V}_J^2 d_o \rho_g}{\sigma_l} \leq 3.7 \tag{5}$$

The constant on the right side of equation (5) may not be exact even in a completely inviscid situation since it assumes that the diameter of the gas cavity is d_o, the nozzle diameter. In fact, the diameter of the gas cavity is greater than d_o, which would tend to increase the constant of 3.7 in equation (5). Despite this limitation, the importance of equation (5) is that it yields an inviscid criterion for stability.

The term appearing on the left side of equation (5) appears in many fluid dynamic applications associated with the effects of capillary forces and is defined herein as a modified Weber number:

$$We_M = \frac{\overline{V}_J^2 d_o \rho_g}{\sigma_l} \leq 3.7 \qquad (6)$$

Equation (6) indicates that the ratio of the inertial forces of the jet to the capillary forces associated with the liquid surface must not exceed a critical value in order to maintain stability. At the point where instability commences, the modified Weber number is defined as critical.

Viscous Dependence

The previous analysis yields an inviscid criterion for stability, namely, that the modified Weber number must remain less than some critical value. From the outset, it was expected that viscous forces associated with the gas jet would be significant in determining the cavity stability characteristics during weightless conditions. The reason for expecting the viscous forces due to the gas jet rather than the viscous forces in the liquid to be the most significant was because the magnitude of the gas velocity and, hence, velocity gradient and shear stress will be much greater than that associated with the bulk liquid. It was expected that the dimensionless parameter associated with the viscous nature of the gas jet would turn out to be the Reynolds number. The following analysis was conducted which shows that the Reynolds number was the viscous parameter and adds the effect of viscous forces to the previous analysis.

The Buckingham π theorem, which can be found in reference 3, indicates that the number of independent nondimensional groupings is equal to the number of important system parameters minus the number of independent variables required to describe these parameters. The important system parameters in this study were the average gas jet velocity at instability $\overline{V}_I$, gas density ρ_g, gas viscosity μ_g, nozzle diameter d_o, and liquid surface tension σ_l. These parameters can be expressed in terms of three fundamental dimensions, mass, length, and time. Application of the Buckingham π theorem, therefore, yields two important nondimensional groupings that can be written in the following functional form:

$$\frac{\overline{V}_I^2 d_o \rho_g}{\sigma_l} = f\left(\frac{\rho_g \overline{V}_I d_o}{\mu_g}\right) \qquad (7)$$

Both these groupings are based on the variables at the point at which instability commences. The first of these is the critical modified Weber number, and the second parameter is the Reynolds number

$$Re = \frac{\rho_g \overline{V}_I d_o}{\mu_g} \tag{8}$$

which should yield the viscous dependence on the critical modified Weber number. In experimental application, both the critical modified Weber number and the Reynolds number are the important scaling parameters to examine concerning the instability effects during weightlessness.

The functional dependence of the critical modified Weber number on the Reynolds number cannot be determined before the fact but must come from experiment. It will be the purpose of this study to examine first whether the critical modified Weber number yields a stability criterion and is the correct nondimensional grouping to consider and second what the form of the viscous dependence is in terms of the Reynolds number.

APPARATUS AND PROCEDURE

A detailed description of the 2.2-Second Zero-Gravity Facility and the experimental apparatus and procedure used is given in reference 1. Briefly, the experimental investigation utilized a flat-bottomed, 19-centimeter-diameter cylindrical container filled with the test liquid, distilled water. Circular brass nozzles with inside diameters of 0.127, 0.191, 0.254, and 0.318 centimeter were located above the liquid surface and at right angles to it. Nitrogen was used as the test gas that passed through the brass nozzle and subsequently impinged on the liquid surface. The physical properties of both the gas and the liquid were taken at 20° C.

The contact angle that the liquid surface makes with the test container surface was maintained at 90° (as described in ref. 1) so that the liquid-gas interface remained flat during impingement. The 90° contact angle was the most desirable since the resulting formation time from a normal-gravity to a weightless environment is zero. Other contact angles require finite formation times for the liquid to reach a static equilibrium configuration. Especially in cylinders with diameters of 19 centimeters, choice of other angles would not be feasible for obtaining a quiescent liquid-gas interface prior to impingement. This choice had the added advantage of allowing the distance between the liquid surface and the nozzle to be kept less than three diameters.

The experiment package used in this study is shown in figure 2. The motion of the liquid-gas interface during impingement was recorded for each test on motion picture film.

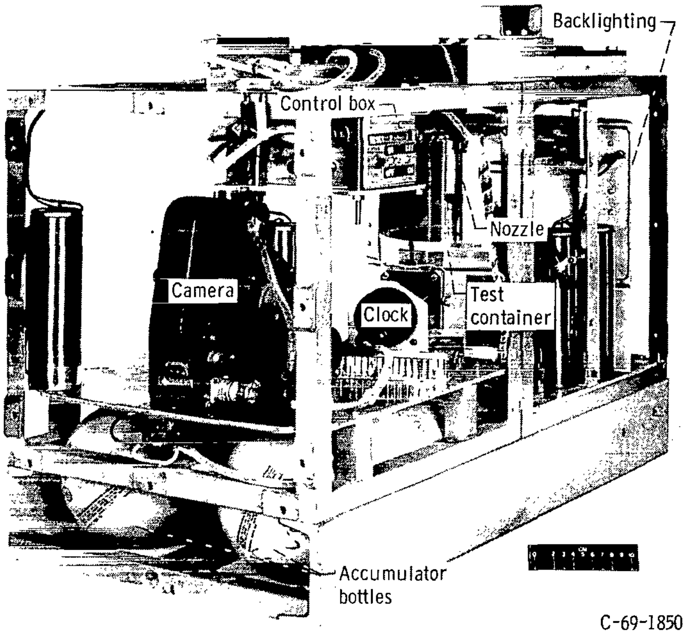


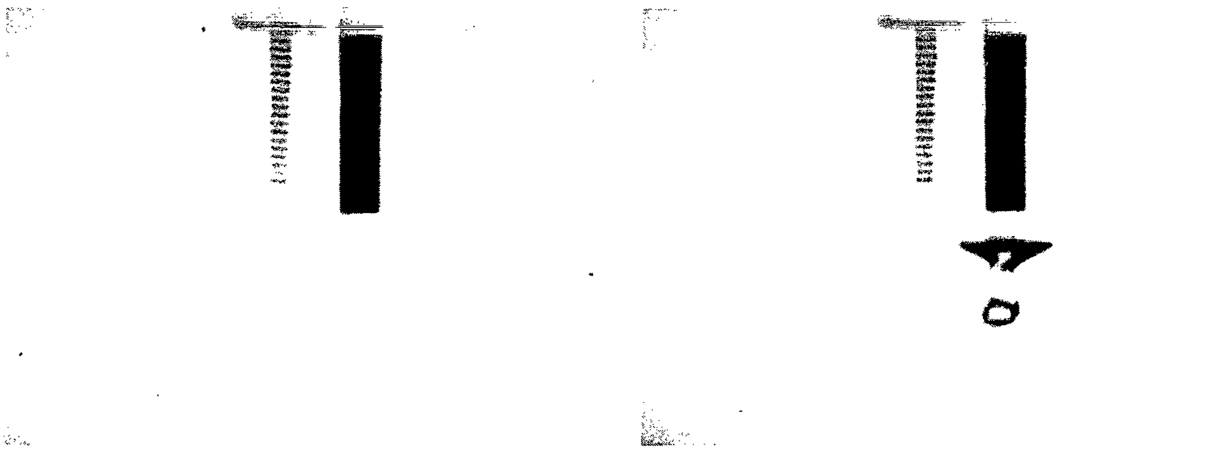
Figure 2. - Experiment package.

RESULTS AND DISCUSSION

Description of Gas Impingement Phenomena

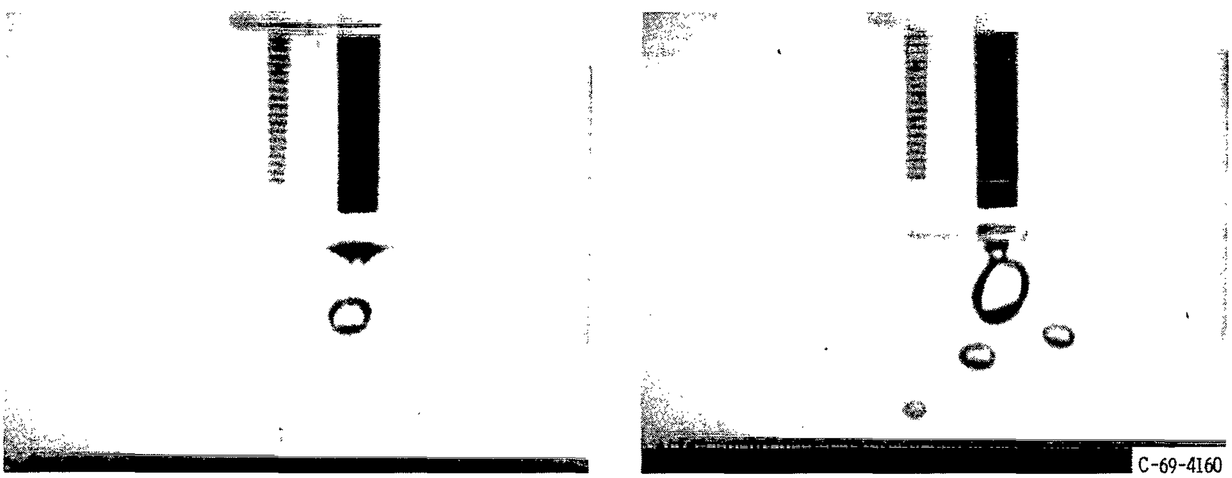
During weightlessness for low gas velocities, a stable oscillating cavity is formed when a gas jet impinges normally on a liquid surface (ref. 1). In reference 1, the average depth of penetration into the liquid surface was correlated with the gas jet momentum and the liquid surface tension (see eq. (1)). When the gas velocity becomes high, however, the gas cavity becomes unstable. When instability occurs, small bubbles pinch off from the cavity and become entrained in the liquid because of the absence of buoyancy forces. The occurrence of cavity instability is shown in figure 3. In figure 3(a), the configuration of the liquid-gas interface during weightlessness is shown to be completely flat, as it would be under normal-gravity conditions. The distance between the nozzle tip and the liquid surface was preset to remain less than three nozzle diameters.

In figure 3(b), with the initiation of gas impingement, the jet is shown penetrating into the liquid surface. In figure 3(c), the cavity necks down and a bubble pinches off resulting in an unstable configuration. At the instant the bubble pinches off from the cavity, the cavity exhibits an increased degree of both lateral and vertical oscillations in contrast to its stable oscillating behavior at lower gas jet velocities. Increased time in weightlessness, as typified by figure 3(d), shows that a number of bubbles pinch off from the cavity and become entrained in the bulk liquid. These bubbles either remain in the



(a) Liquid-gas interface position during weightlessness. Time, 0.31 second.

(b) Gas impingement. Time, 0.38 second.



(c) Bubble pinch-off. Time, 0.57 second.

(d) Configuration near termination of test. Time, 1.79 seconds.

Figure 3. - Occurrence of bubble pinch-off. Average jet velocity, 1260 centimeters per second; nozzle diameter, 0.127 centimeter; test liquid, distilled water; distance between nozzle tip and liquid surface, 0.3 centimeter; Reynolds number, 1071.

bulk liquid as single bubbles or coalesce with their neighbors, which is in contrast to their behavior in a normal-gravity environment, where the buoyancy forces drive the bubbles back up to the liquid-gas interface.

Cavity Stability Results

From each test run, a determination was made of whether or not the gas cavity was stable. The results of these tests are shown in figure 4, where the dependence of stability on the average jet velocity and the nozzle diameter is indicated. Nozzle diameters of

0.127, 0.191, 0.254, and 0.318 centimeter were used. A line drawn through these data separates the regions of stable-oscillating and unstable bubble pinch-off conditions. As can be seen from figure 4, the velocity at which the gas cavity becomes unstable decreases

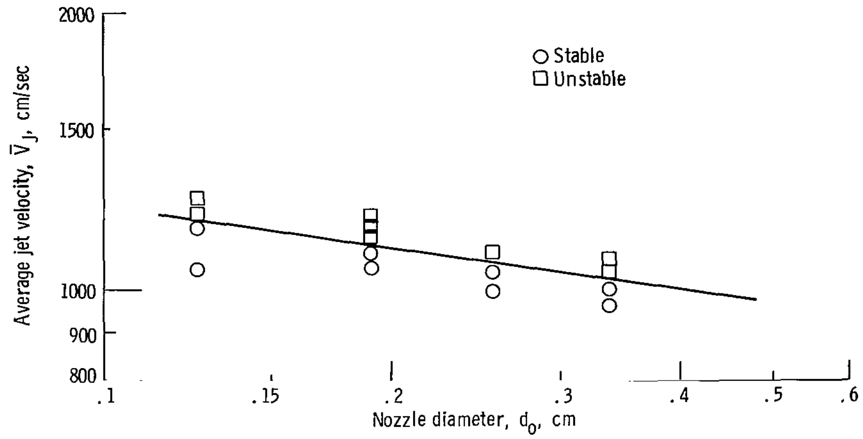


Figure 4. - Stability dependence on average jet velocity and nozzle diameter.

with increasing nozzle diameter. This result agrees with the inviscid analysis (see eq. (5)), although the dependence is not quite as strong as this analysis indicates.

A correlation of the data in terms of the critical modified Weber number, as described by equation (6), and the Reynolds number, as described by equation (8), was attempted. The results are shown in figure 5. A line faired through the data, delineating the regions of stable-oscillating and unstable bubble pinch-off flows, was drawn. An empirical equation correlating the data over the range of test variables was obtained:

$$We_{M_{cr}} = \frac{Re^{0.8}}{89} \tag{9}$$

As can be seen from this equation, the critical modified Weber number is not a constant as previously predicted by the inviscid analysis but varies with Reynolds number. The critical modified Weber number is a strong function of the viscous forces associated with the bubble pinch-off process.

No spraying was observed in the tests conducted during weightlessness in this study. These results are similar to those obtained in reference 1, where no spraying of liquid droplets from the gas cavity was observed. This point is mentioned since spraying is a very common occurrence under normal-gravity conditions.

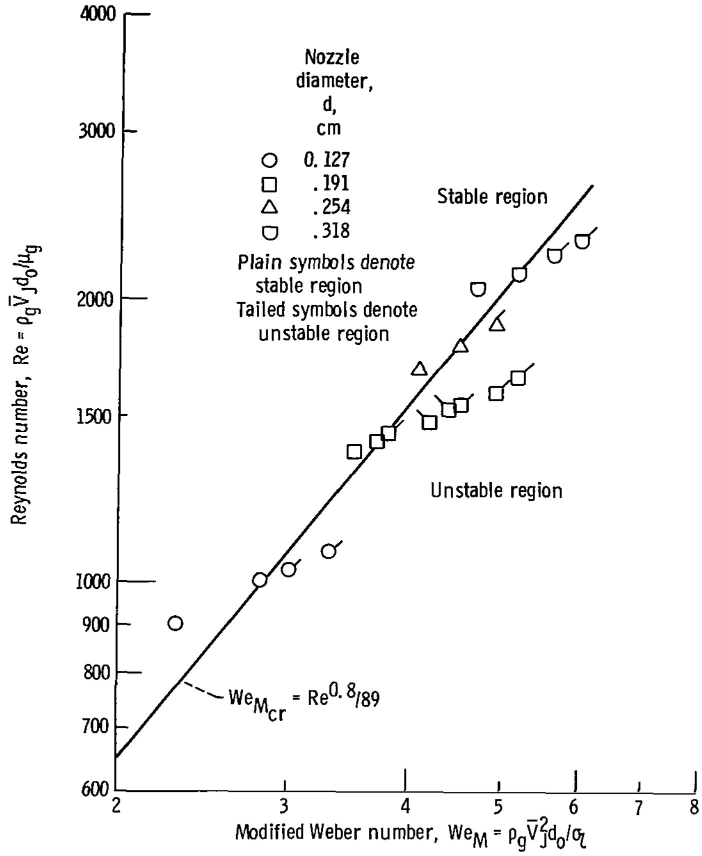


Figure 5. - Dependence of critical modified Weber number on Reynolds number.

SUMMARY OF RESULTS

An experimental investigation was conducted in the NASA Lewis Research Center 2.2-Second Zero-Gravity Facility to determine the cavity stability criteria for gas jet impingement on a liquid surface during weightless conditions. The contact angle on the test container surface was restricted to 90° such that the liquid-gas interface remained flat and stationary prior to impingement during weightlessness. The distance between the liquid surface and the circular nozzle was less than three nozzle diameters. The nozzles tested had inner diameters ranging from 0.127 to 0.318 centimeter. Nitrogen was employed as the test gas and water as the test liquid. This study, which employed laminar parabolic jets, yielded the following results:

1. The velocity at which the cavity becomes unstable during gas impingement on a liquid surface decreases with increasing nozzle diameter.

2. An inviscid analysis was used to derive analytically a critical modified Weber number $We_{M_{cr}} = \rho_g \overline{V}_J^2 d_o/\sigma_l$, where $We_{M_{cr}}$ is the critical modified Weber number,

ρ_g is the gas density, $\overline{V}_J$ is the average jet velocity, d_o is the nozzle diameter, and σ_l is the liquid surface tension. The critical modified Weber number yielded a parameter for determining the regions of stable oscillating and unstable bubble pinch-off flows.

3. The critical modified Weber number was experimentally shown to be a function of the Reynolds number and was empirically determined from the data to be $We_{M_{cr}} = (Re^{0.8})/89$. The Reynolds number is $Re = \rho_g \overline{V}_J d_o / \mu_g$, where μ_g is the gas viscosity.

4. No spraying of liquid droplets from the gas cavity was observed under weightless conditions over the range of variables tested. This characteristic was also observed in previous studies.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, June 3, 1970,
124-08.

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